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14. ABSTRACT

The generation of ultra-stable modelocked pulses in the 1550 regime is required for high resolution signal processing applications that include electro-optic sampling, transient probes, and optical clocks. More recently the frequency combs comprising these pulses have been applied to innovative methods of Arbitrary Waveform Generation (AWG) in the optical domain [1]. Temporal stability in certain of these applications assumes the utmost importance. A proven approach to address the key issue, entails a significant reduction in system dimensions by means of an Erbium-Doped Waveguide Amplifier (EDWA) [2,3,4] , which can minimize adverse effects of thermal gradients. To further enhance the long term stability, a Pound-Drever-Hall (PDH) technique can be used to lock the laser to a known frequency reference, in effect allowing the cavity to compensate for the laser's drift. We report for the first time to our knowledge the result of incorporating PDH stabilization in an Erbium-Doped Waveguide Laser (EDWL) [5,6], and compare this with a commercially available Erbium Doped Fiber Laser (EDFL).

15. SUBJECT TERMS

Keywords: erbium-doped, mode-locked, etalon, Pound-Drever-Hall

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Frequency stabilization of a waveguide laser using Pound-Drever-Hall

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ABSTRACT

The generation of ultra-stable modelocked pulses in the 1550 regime is required for high resolution signal processing applications that include electro-optic sampling, transient probes, and optical clocks. More recently the frequency combs comprising these pulses have been applied to innovative methods of Arbitrary Waveform Generation (AWG) in the optical domain [1]. Temporal stability in certain of these applications assumes the utmost importance. A proven approach to address the key issue, entails a significant reduction in system dimensions by means of an Erbium-Doped Waveguide Amplifier (EDWA) [2,3,4] , which can minimize adverse effects of thermal gradients. To further enhance the long term stability, a Pound-Drever-Hall (PDH) technique can be used to lock the laser to a known frequency reference, in effect allowing the cavity to compensate for the laser's drift. We report for the first time to our knowledge the result of incorporating PDH stabilization in an Erbium-Doped Waveguide Laser (EDWL) [5,6], and compare this with a commercially available Erbium Doped Fiber Laser (EDFL).

Keywords: erbium-doped, mode-locked, etalon, Pound-Drever-Hall

1. INTRODUCTION

Mode-locked lasers in the 1550 nm regime continue to experience ever increasing uses as laser source, detection, and diagnostic technologies mature. However a full realization of some of the demanding applications is limited by stability considerations. A single longitudinal mode frequency comb component, for example, can exhibit a narrow spectral linewidth centered, at a precisely known frequency. However, neither that resolution, nor accuracy, can be realized in any practical application unless those parameters are stable over the requisite measurement time interval, to within the tolerance defined by the particular measurement application. We address in particular the frequency drift for the spectral envelope of the modelocked pulses, that being the first step required to utilize all of the frequency components offered by the mode spectrum. Temporal jitter and phase noise measurements are also performed to fully characterize the effects of active cavity compensation on the temporal stability of this particular source configuration. Based on prior experience with EDFLs [5,6] an intracavity etalon is included to effectively filter cavity super modes [7,8,9] that result from making the modelocked frequency a high harmonic of the fundamental cavity. The use of this ultra-compact gain medium permits to reduce the cavity size and temperature effects, although standard telecom fiber was still used to connect the other components in the cavity. Various temperature control schemes have been used to minimize fluctuations to the cavity. The experimental results presented therefore incorporate an intracavity etalon for supermode suppression, and Pound-Drever-Hall method to stabilize the frequency spectrum of an ultra-compact EDWL.

2. APPLICATIONS

The selection of 10 GHz as the modelocked frequency accomplishes a dual purpose:

1. The physical construction, data rate, and pulse duration are all suitable for a versatile high rate digital source for laboratory and non-laboratory use.
2. The spectral separation approaches the maximum that can be spanned by available optical phase modulators. Full access to a substantial spectral interval is provided with high bandwidth and access rate. This is an initial step toward realization of a practical AWG format.

3. CONFIGURATION

3.1 Waveguide Laser

Our laser gain medium consists of an erbium doped multi-component glass waveguide amplifier (EDWA) with complete packaged dimensions of 25x35x6 mm, and a folded gain path length [2,4,5] of 25 cm. Incorporated in that device is a 980/1550 nm wavelength division multiplexer (WDM) and a 980 nm rejection filter at its output. The waveguide was pumped with 200 mW from at 980nm diode laser (Corning Lastron PN CLT3). After the output of the EDWA there were two optical circulators (Finisar PN 10121415) to establish unidirectional propagation as well as high isolation from reflections in an adjacent temperature stabilized Fabry-Perot etalon (Micron Optics PN FFP-1). In-line polarization control (Newport PN F-POL-IL) was used to maximize transmission through the etalon. The etalon, with free spectral range (FSR) of 10.2 GHz and bandwidth of 32 MHZ, is used to suppress the cavity harmonics in the laser. To polarize the cavity and serve as an input/output for the PDH, a fiber based polarizing beam splitter (PBS__Canadian Instrumentation and Research PN 968P) followed the etalon. Output from the cavity came from the 90/10 optical splitter (Gould). A fiber stretcher also by Canadian Instrumentation and Research tuned the cavity length by means of the PDH loop. Another in-line polarization controller oriented light entering the lithium niobate amplitude modulator (JDS PN 10020465), which was driven at 22 dBm with an RF signal generator (Agilent PN E8257C) to mode-lock the laser. A tunable bandpass filter (JDS Fitel PN TB1500B) with 3 dB bandpass of 5nm selected the operating wavelength. An additional optical circulator was used to isolate the gain medium, and its output was fiber-fused to the input of the EDWA. After the output coupler, an Erbium-doped fiber amplifier (EDFA__Pritel PN LNHPFA-30) was used to amplify the output prior to being sent to 1x4 optical splitters and various diagnostic equipment. The complete laser configuration is shown in figure 1.

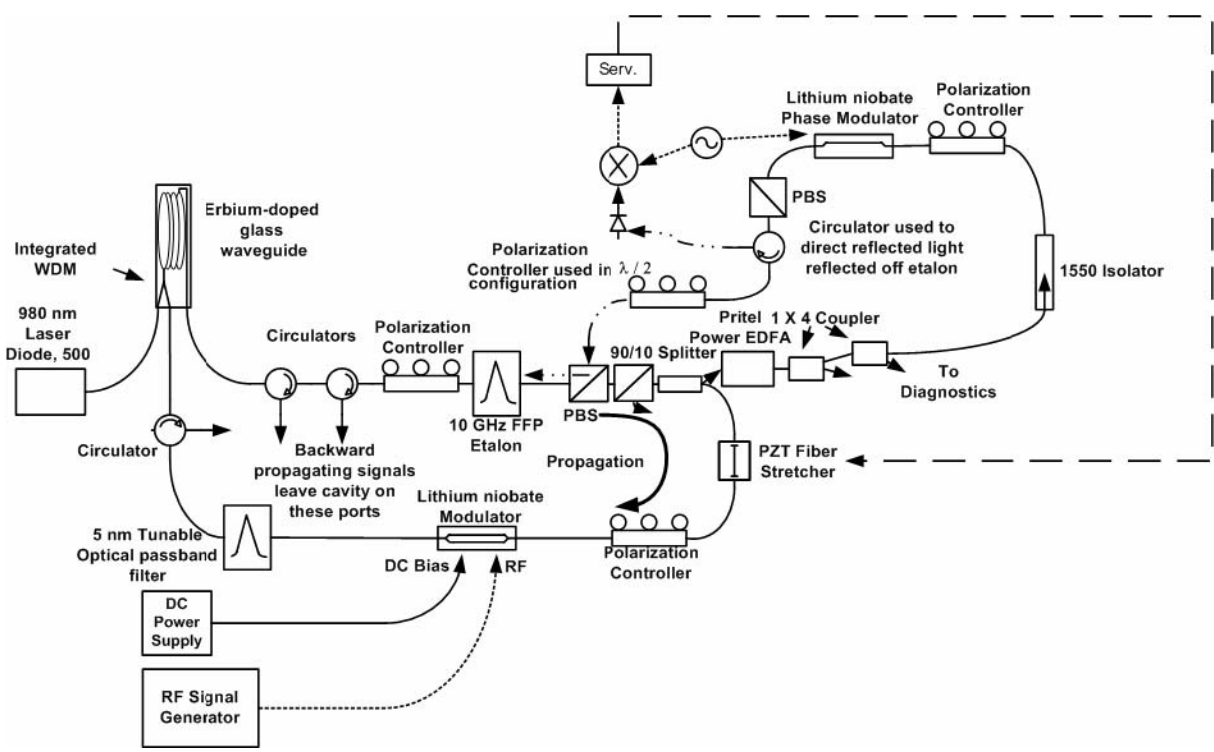

Figure 1: EDWL cavity with PDH loop.

3.2 Pound-Drever-Hall

The PDH stabilization method uses the amplified output of the laser cavity as an input to the feedback loop. The polarization of incoming light is set with an in-line polarization controller before entering a lithium niobate phase modulator (JDS PN 21004570). After the phase modulator, a fiber based polarizing beam splitter is used to orient the polarization feedback into the cavity. An optical circulator (Finisar) and a polarization controller (at half-wave retardation) complete the loop. The output of the polarization controller is then fused to the TE polarized output port of the PBS immediately following the etalon. The TE polarized reflects in turn from the PBS, the etalon, and the PBS again, before retracing its path to the circulator, where exiting TE polarization is detected (Discovery PN DSC30S). This output is mixed with the signal driving the phase modulator, and the resultant difference signal goes to a multi-function controller with Proportional, Integral, and Differentiation (PID) features. The voltage leaving the PID is amplified appropriately and delivered to the PZT stack for the fiber stretcher; the change in cavity length is in direct proportion to the received error signal.

4. EXPERIMENTAL RESULTS

A degree of environmental isolation of the laser was provided by a Plexiglas enclosure to reduce air currents; but no stabilization method for temperature effect, other than PDH, was incorporated at this time. The laser was first optimized without any optical input into the PDH stabilization loop, and then with the PDH loop operating.

4.1 EDWL without input into PDH loop

The cavity polarization was oriented and optimized with reference to the polarizing beam splitters in the cavity, transverse magnetic (TM). The etalon transmission was then maximized by adjusting the input polarization, and the laser wavelength was selected by setting the (5nm) tunable optical bandpass filter. Transmission through the amplitude modulator was optimized with another polarization controller. Diagnostic monitoring of the output power, polarization, optical and RF spectra, RF spectrum and pulse train provided feedback in real time to monitor mode-locked performance. After some initial settling, 2 nm drifts in the optical spectrum were typically observed over 5 minute intervals with somewhat cyclic behavior. The average laser output power was ~300 μW with a peak pulse power of 2.8 mW. This is consistent with the known component losses, the saturated output power of the EDWA, and the 90/10 output coupler. Cavity losses also exhibited a clear effect on the spectral width, and when

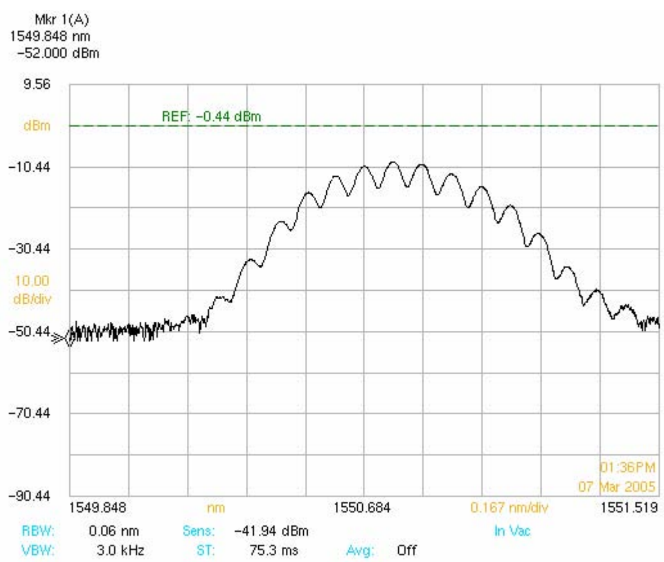

Figure 2: Optical spectrum of the EDWL.

minimized the full width half max (FWHM) was ~ 0.40 nm. This is shown in figure 2., and a higher resolution trace from a scanning Fabry-Perot etalon is shown in figure 3, where the 10 GHz separation of the modelocked longitudinal modes is exhibited. The double and triple peaks on the right side of the trace are due to 1st and 2nd etalon orders.

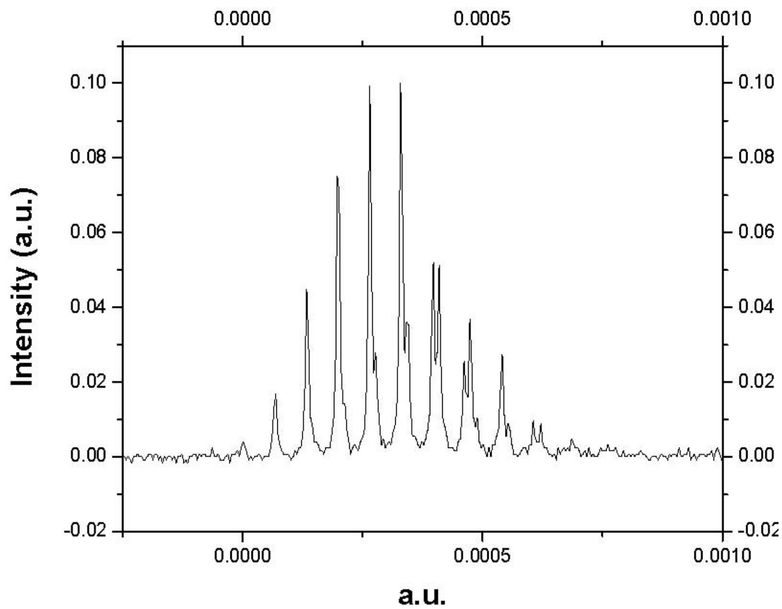

Figure 3: Optical Spectrum taken with the scanning Fabry-Perot.

With the laser optimized the (unresolved) 21 ps pulse train can be displayed on a 50 GHz digitizing oscilloscope. Assuming a Gaussian pulse shape the autocorrelation trace indicates a FWHM of ~11 ps. The time bandwidth product of 0.54, approximately 1.3X that of 0.44 for the theoretical Gaussian case, shows some departure from the transform limit, as is expected without internal or external dispersion compensation in this cavity. The optical pulse train can be seen in figure 4, and the autocorrelation trace in figure 5.

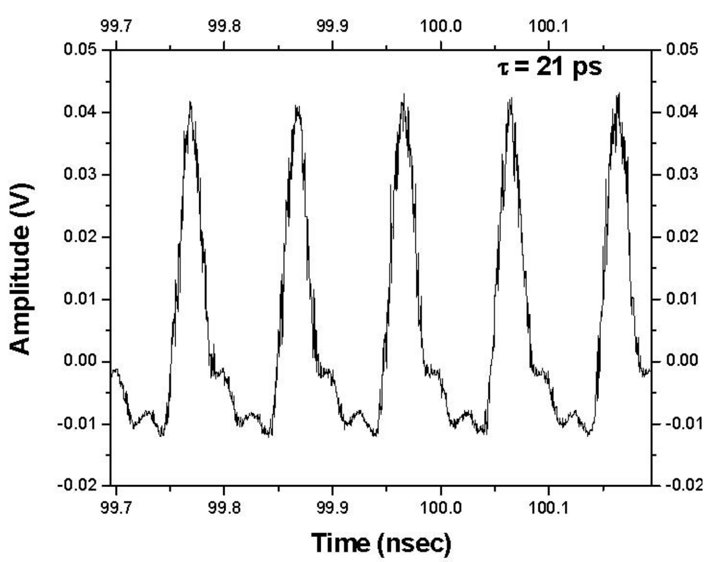

Figure 4: Optical Pulse Train of the EDWL

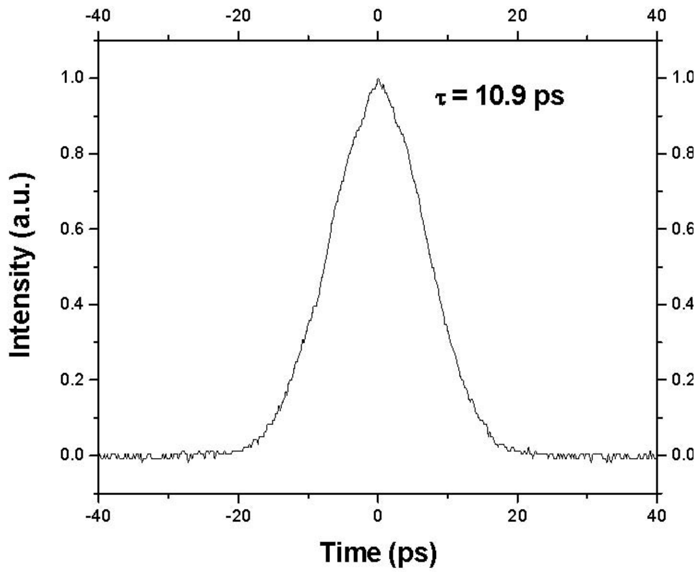

Figure 5: Autocorrelated EDWL pulse.

During the optimization process the cavity length was minimized so as to increase the fundamental frequency of the cavity. This shifts any harmonics adjacent to the locked one, spectrally farther from the center of the etalon's bandpass. The steep slope of the etalon's bandpass further suppress any remaining harmonic. With components fully aligned so that one of the cavity harmonics matched the peak transmission of the etalon, the suppression of all other harmonics was below the level of the RF spectrum analyzer noise floor. In figure 6 the RF spectrum is shown with a suppression greater than 92 dB.

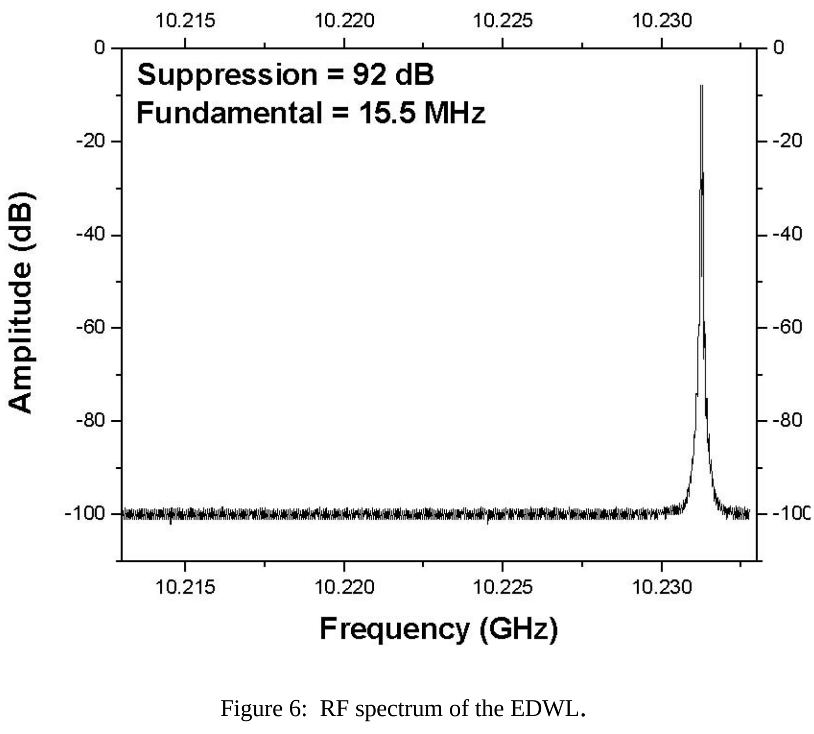

Figure 6: RF spectrum of the EDWL.

4.2 EDWL with input to PDH loop

With the EDWL aligned and the lab environment relatively constant, the PDH loop was connected. The proper operation and the effect of the error signal are evident in Figure 7. The desired performance is confirmed by injecting a swept CW laser signal into the input to the PDH loop and monitoring the output of the mixer for the error signal. Driving the phase modulator at 400 MHz yields 400 MHz sidebands on the CW carrier, and those lying outside the etalon's passband are reflected and propagate back along the injected path. The sidebands are mixed with the 400 MHz reference and the output of the mixer gives the error signal. To characterize the loop the phase modulator was driven at 110 MHz, which is still outside of the etalon's passband. The PDH loop was

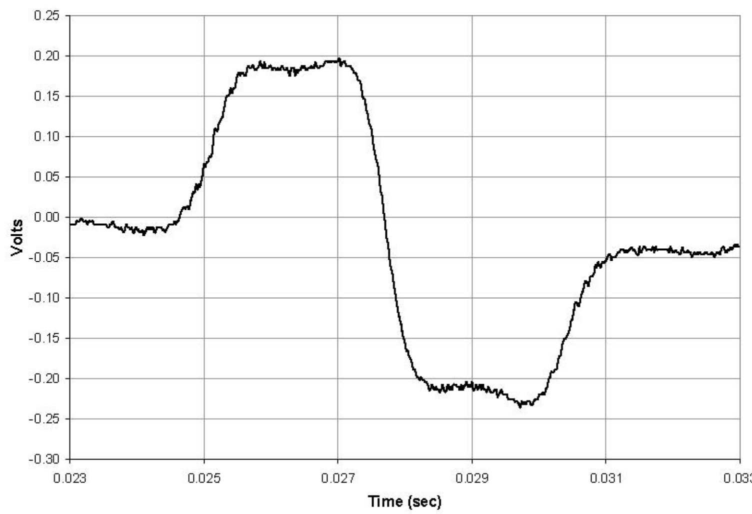

Figure 7: Error signal out of the mixer from the PDH loop.

connected and the cavity monitored to confirm that no feedback induced instability resulted. The output of the erbium doped fiber amplifier (EDFA) was injected into the loop; with 10 mW in, ~200 µW was detected on the output fiber of the circulator. Polarization alignment was readjusted to ensure that TM was entering the loop, and that the polarization controller used as a half wave plate put out transverse electric (TE) polarization. The PID controller could then be activated and the laser diagnostics monitored for instability effects. The spectral shape, RF spectrum, pulse shape and width were all observed to remain relatively constant in time. The degree of drift in the center of the optical frequency was noticeably reduced, and the active compensation effects could be observed directly. Furthermore the stable operating time before characteristics deteriorated was observed to exceed an hour. PDH compensated cavity length drift but cannot compensate other effects such as polarization evolution with time in the fibers. It was confirmed that even when the pulse characteristics were finally lost, realignment of polarization was sufficient to restore them. Since the fiber connecting the components was not all polarization maintaining, that is also to be expected. A useful result of this experiment is to permit us to distinguish to some degree, which effect causes instability. It also indicates that to achieve even longer term stability, beyond an hour or so, polarization maintaining components are most likely required throughout the system.

The PDH enhanced EDWL stability was quantified by detecting the RF beat signal between the EDWL output and that of a CW laser which exhibits a narrow linewidth as compared with the system lasers under test. This procedure produces a narrow central peak at 10 GHz due to beating of the mode-locked combs. Equal sidebands are created from the CW laser beating with different longitudinal modes of the laser. Figure 8 shows the beat signals with (+/- 5 MHz) and without (+/- 10 MHz) the loop and "max hold" display on the RF spectrum analyzer for 2 minutes. Figure 9 shows a comparison of the beat notes for a commercial EDFL laser (+/- 20 MHz), which uses all polarization maintaining (PM) optics. The width of the beat signal indicates the laser is still mode-locked but the optical combs are freely moving.

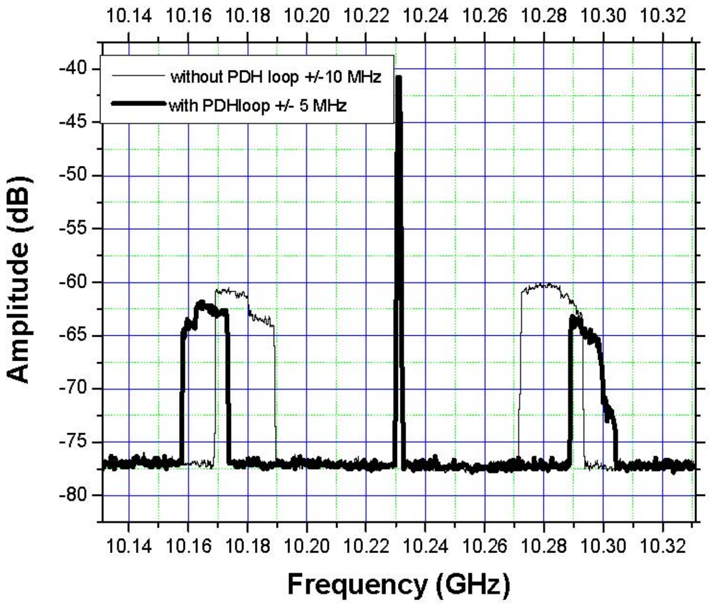

Figure 8: Beat signal of the EDWL and CW laser.

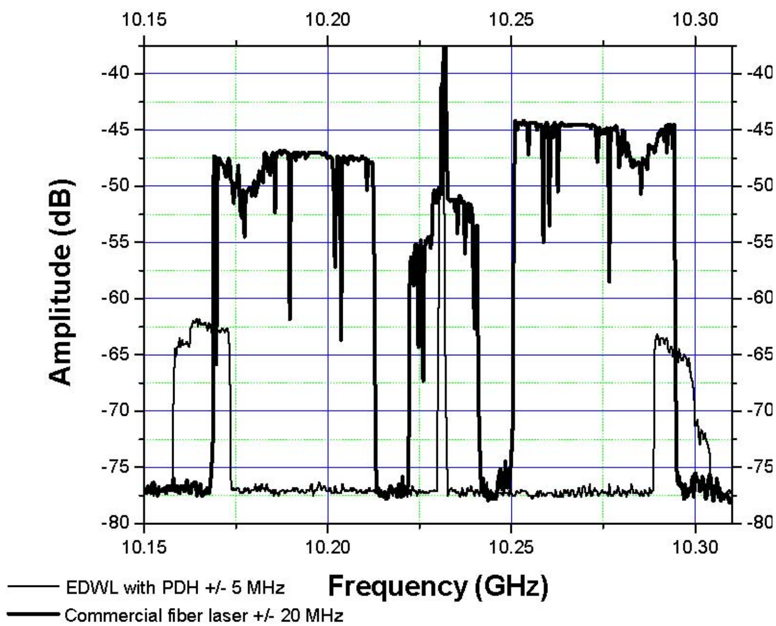

Figure 9: Beat signal of a commercial fiber laser and CW laser.

Residual phase noise measurements of the EDWL without and with the PDH loop connected were obtained [10,11,12]. Only slight improvement was noticed in the timing jitter when the PDH loop was connected, whereas a significant increase was noticed in time of stability for EDWL. Figure 10 and 11 are single-sideband residual phase noise measurement taken without and with the PDH connected. The peak at 10 MHz is the 10 MHz reference signal

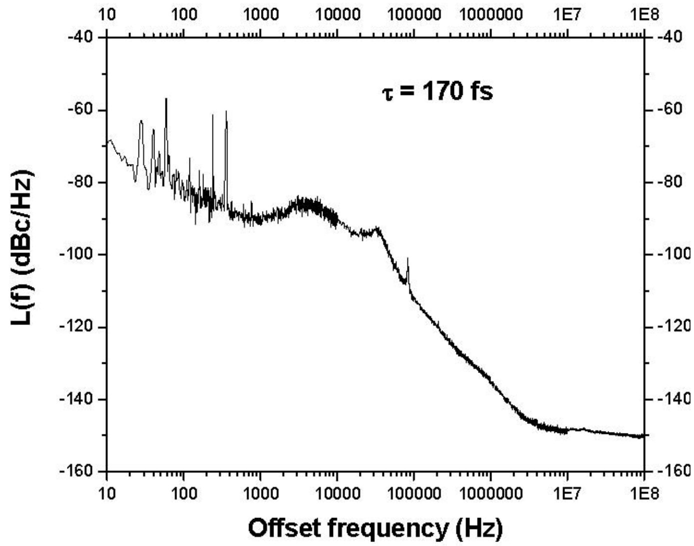

Figure 10: EDWL without PDH loop.

used to phase lock the RF generators together and the increase in low frequency noise is caused from the RF amplifiers used to raise the signal levels required by the measurement equipment.

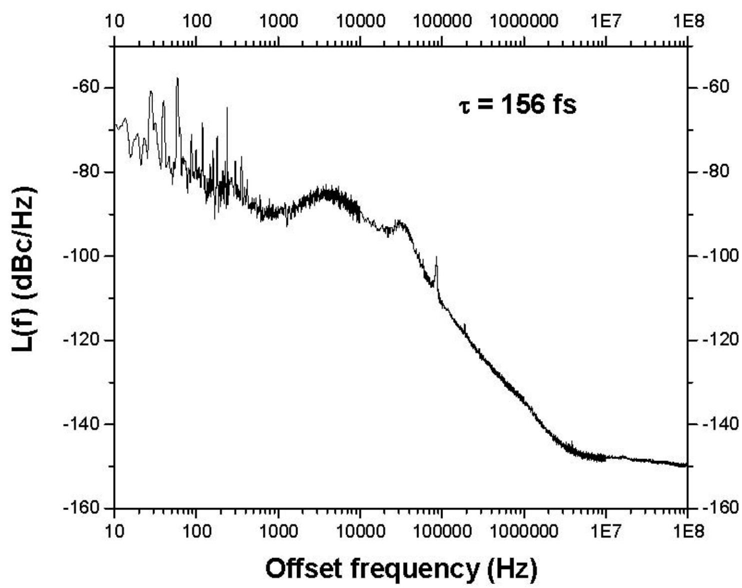

Figure 11: EDWL with PDH loop.

5. SUMMARY

A harmonically mode-locked fiber laser was constructed with an EDWA gain medium, reducing the gain length to 25 cm and the packaged length to 25 mm. The EDWL had an optical spectral width of 0.40 nm and a pulse width of ~11 ps giving a time-bandwidth product of 0.54. The suppression of the cavity harmonics relative to the 10.2 GHz mode-locked rate was > 92 dB. Timing jitter of the laser was 170 fs without the PDH loop and 156 fs with the PDH loop. The cavity harmonics inherent to harmonically mode-locked lasers were suppressed with an intracavity Fabry-

Perot etalon. Utilizing that same intracavity etalon as a reference the Pound-Drever-Hall frequency stabilization technique was used to stabilize the EDWL. Stability time was increased by 2X, with the laser staying stable and locked in excess of 1 hour. The increased understanding and ability to control parameters affecting stability, enables broader use of mode-locked fibers, particularly in the most demanding applications.

6. CONCLUSIONS

The PDH stabilization demonstrated effective temperature compensation for an extended period, before instability resulted from polarization evolution in standard fiber used to connect the components. For the shorter time periods, remarkably, the PDH enhanced stability was comparable to that of a commercial EDFL based on PM optics throughout. The strong implication is that if we substituted PM fiber in our laser design, the stability would likely exceed its present performance because of more stringent polarization control. Further effort to eliminate nearly all connecting fiber length, and PM use in what remains, would yield greater stability than what is presently available, and also the most compact system yet achieved. The exact nature of the applications being explored in optical AWG may influence the degree to which that may be pursued in future work.

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